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Haldor W.C. Aamot

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PREFACE

The work reported here was conducted as part of the Cold Regions Research and Engineering Laboratory's (CRREL) in-house development of instrumented thermal probes. The work was performed in the Measurement Systems Research Branch (Mr. William H. Parrott, Chief) of the Technical Services Division (Mr. B. Lyle Hansen, Chief), CRREL, U.S. Army Terrestrial Sciences Center (USA TSC). Mr. Haldor W.C. Aamot, Research Mechanical Engineer, was project engineer. This report was published under DA Project No. 1T061101A91A, *In-House Laboratory Independent Research.*

Mr. John Kalafut, Electrical Engineer, assisted with the winding and tested the electrical characteristics of the coils. The Laboratory's machine shop fabricated the necessary mandrels. Mr. Frederick J. Sanger, Experimental Engineering Division, provided constructive review of the manuscript.

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ABSTRACT

Thermal probes, like certain rockets and torpedoes, contain power and guidance wire for trailing payout. This wire must be wound into long, slender coils to obtain a slim profile, with a winding pattern of high density and perfect regularity to assure reliable payout from inside the mandrel-less coils. The development of a winding capability using the orthocyclic method solved problems of maintaining complete control of the winding pattern throughout the whole coil. A collapsible, grooved mandrel was developed which can be readily removed from the finished coil for re-use. Coils were wound with diameters of up to 8.5 cm and lengths up to 79 cm with wire lengths to 2100 m.

WINDING LONG, SLENDER COILS BY THE ORTHOCYCLIC METHOD

by

Haldor W.C. Aamot

INTRODUCTION

Thermal probes used to penetrate polar ice sheets (Philbert, 1962; Aamot, 1968) are long and slender to minimize resistance to penetration. Their shape requirements are analogous to those of aerodynamic and hydrodynamic bodies (e.g. rockets, torpedoes). The internally stored conductors are precision wound for maximum packing density and reliable payout from the inside of the mandrel-less coils. The coils have a high length-to-diameter ratio. The orthocyclic winding method (Lenders, 1961-62) was selected because it meets the requirements of packing density and has the complete pattern regularity necessary for reliable payout. A processor experienced in winding such coils, however, could not be found.

Work was started to develop at CRREL a winding capability for long, slender coils, using the orthocyclic method. The author did the winding in the laboratory's machine shop. This in-house program began in 1964 and was conducted in conjunction with the overall development of the probes.

This report describes the winding equipment and setup, the problems encountered with, and the solutions found for, maintaining the winding pattern correctly throughout the coil, and the design of the collapsible mandrel.

The uniform and reproducible characteristics and the reliable payout feature of such coils suggest other applications.

WINDING PATTERN

The highest packing density in a coil wound from round wire is achieved when all turns in a layer lie in the grooves formed between the turns of the underlying layer. It is intended to achieve, or at least approach, this theoretical maximum density by careful control of the winding process. The perfect regularity of the resulting winding pattern also promises reliable payout from inside the completed coil.

A wire that is closely wound on a smooth mandrel in a single layer forms a helix (e.g. from left to right). The pitch is equal to the wire diameter. In succeeding layers the direction of the helix reverses alternately. A problem develops when the wire follows the pattern of the underlying layer and cannot establish a helix in the opposite direction. Soon the pattern regularity is lost and the winding becomes random.

A regular pattern can be maintained if the helix can be eliminated. The first turn is adjacent to the flange and normal to the axis, i.e. orthogonal. Near the end of the first turn the wire deflects to the side (e.g. to the right) to form a discrete step or crossover. The process repeats itself with each turn. The crossovers are all adjacent and form a crossover line. In the second layer the deflection is in the opposite direction (to the left) and it reverses again with each succeeding layer but all turns remain orthogonal (Fig. 1). This is called the orthocyclic method.

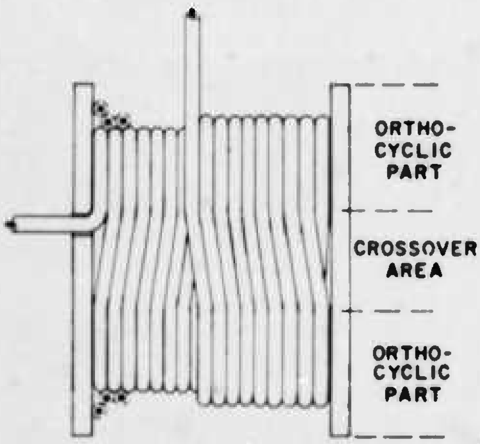

Figure 1. The orthocyclic method uses windings which are normal to the coil axis instead of helical. Each turn has a discrete lateral deflection called a crossover before starting on the succeeding turn. The crossovers are in opposite direction on alternating layers according to the direction of the winding progress. The crossovers in a layer form a line called the crossover line.

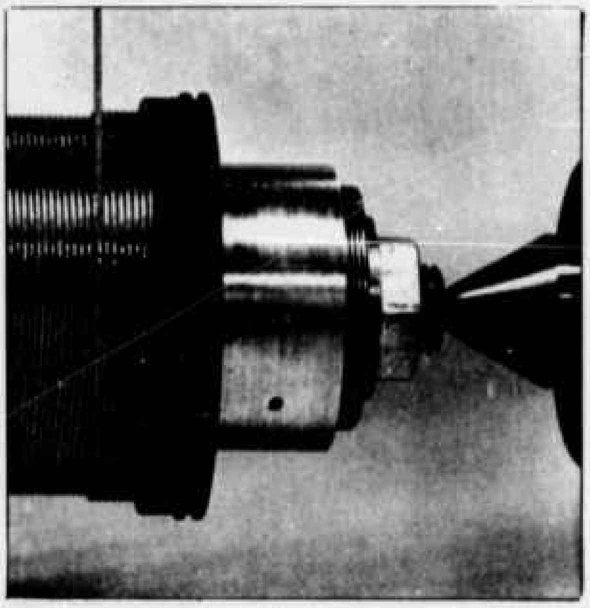

Figure 2. The deflection of each turn and the beginning of the crossover line at the flange are clearly visible. By careful control of the winding process, the perfect regularity of the orthocyclic winding pattern is preserved throughout the whole coil.

The patented LeBus method (LeBus, 1958) accomplishes the same results. The pattern is similar but with crossovers on two sides of the coil. This requires an offset in the mandrel grooving and the flanges; this offset is not necessary with the orthocyclic method.

Another coil with a regular winding pattern is the "universal" coil. This coil has the advantages of being self-supporting and being commonly wound by many processors. The universal method and suitable winding machines are described by Querfurth (1958). The disadvantage of this method is its lower packing factor.

The orthocyclic method was selected because of its high density, its complete pattern regularity, and its basic simplicity. Figure 2 shows the orthocyclic pattern of a coil wound for a thermal probe.. When completed the coil is installed in a shroud and the mandrel is removed. The flanges remain with the coil. The wire pays out from the inside where the winding process began. The close proximity of the coil to its housing walls (shroud) and the resulting favorable heat transfer conditions are maintained until the coil is completely payed out.

WINDING EQUIPMENT AND SETUP

A lathe in the CRREL machine shop was used for winding. A variable-speed motor was not available, but careful control of the clutch permitted smooth and gradual starts. The winding speeds were kept low, generally below 100 rpm, to permit observation of the pattern during winding. The level-wind mechanism was built after the principle described by Lenders, but without a damping device. The freely swinging cantilever arm is guided by the wire which follows the pattern progressing on the coil (Fig. 3). This improvised setup works satisfactorily except for the arc produced by the arm. On a long coil this arc forms a significant angle with the axis of the mandrel, lateral forces develop on the winding pattern and its regularity is affected. A driven

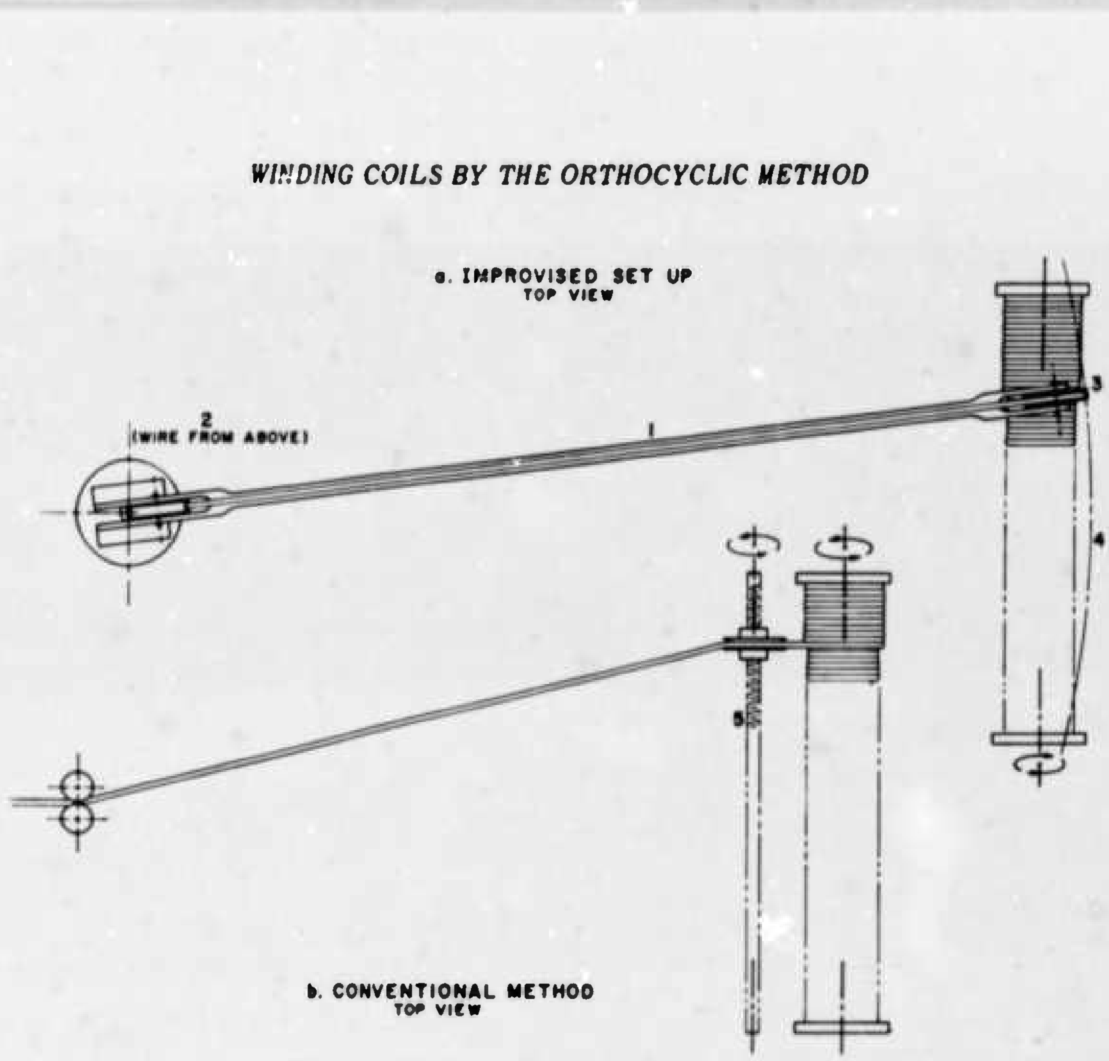

Figure 3. A simple level-wind mechanism consists of a freely swinging cantilever arm (1) with the pivot at 2. The arm is guided by the wire which follows the progressing winding pattern on the coil (3). The arc (4) produced by the arm interferes with the uniformity of the pattern. A driven level wind (5) used on coil winding machines permits the wire to be fed normal to the coil along its entire length by matching the level wind advance to the pattern progress. A better control of the winding pattern is thus achieved.

level wind as used on commercial winding machines with an axis parallel to the mandrel is considered necessary to wind the long coils reliably. As a compromise a freely sliding sheave on a shaft parallel to the mandrel was used with the freely swinging arm which resulted in a small improvement of the winding behavior and permitted successful winding with this simple system.

Figure 4 shows the complete setup. The supply reel on the right has a friction brake to maintain the proper wire tension. The wire runs over a pulley near the top of the A-frame. This pulley cushions the variations in wire tension and acts as a safety device in case the wire jams on the supply reel. The pulley works against a spring and counterweight. The spring is represented by a scale which is used to check the winding tension.

Coils were wound to a finished diameter of about 8.5 cm (3.35 in.) and lengths up to about 79 cm (31.1 in.), as shown, with wire diameters ranging from 0.075 cm (0.030 in.) to 0.190 cm (0.078 in.) and wire lengths to about 2100 m (6400 ft).

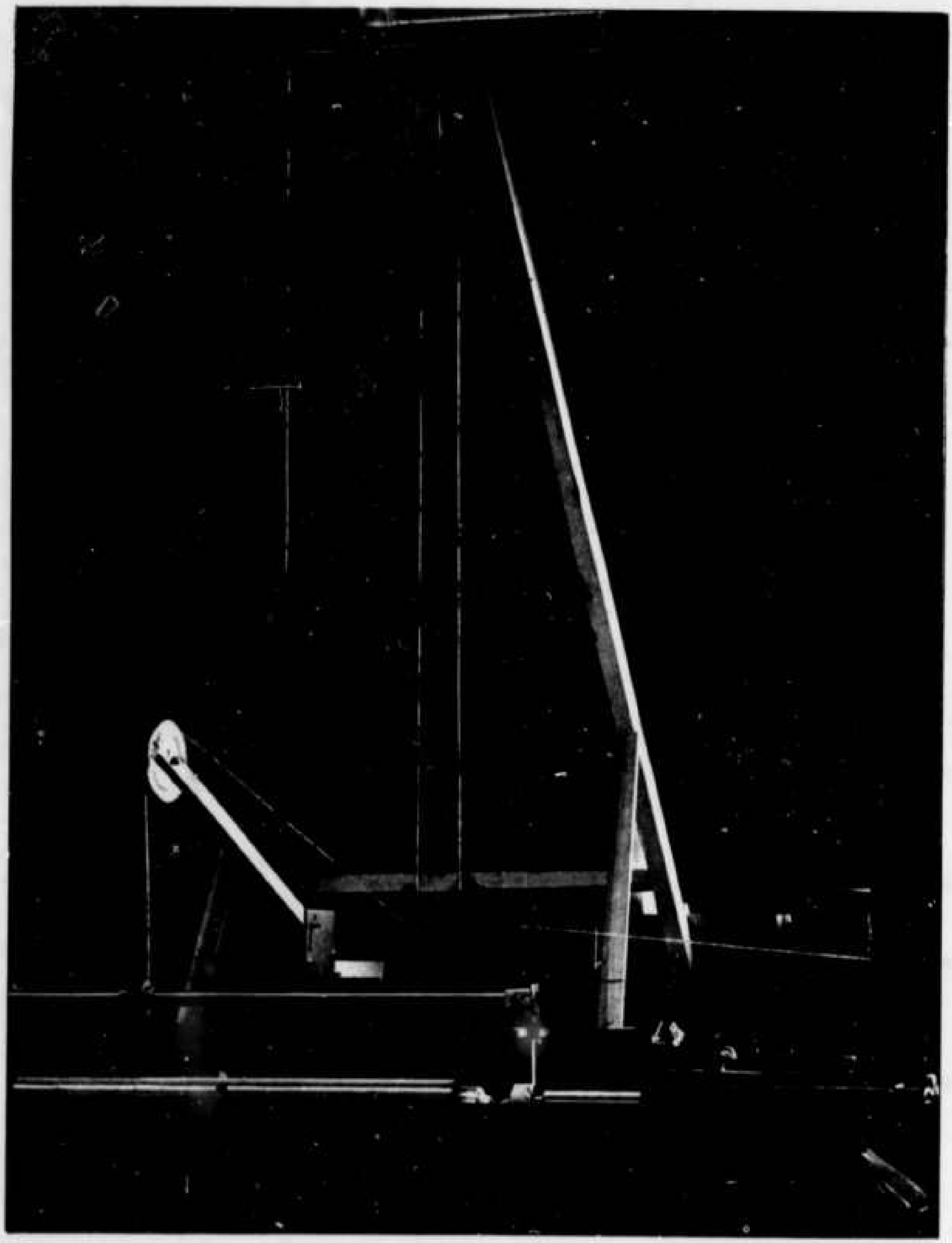

Figure 4. The winding setup in the CRREL machine shop shows the nearly completed coil (1) on the lathe (2). The improvised level wind mechanism (3) guides the wire to the coil. The winding tension control consists of a pulley (4) which is held by a spring (5) for flexibility and a counterweight (6) as a load limit; a friction brake (7) on the supply reel (8) serves to adjust the wire tension.

MANDREL GROOVING

The requirement of an almost perfectly uniform wire diameter to assure a perfectly regular winding pattern throughout the coil was emphasized by Lenders. He demonstrated that the problem is aggravated by the length of the coil, i.e. by the number of turns per layer. The coils for the probes have as many as 600 turns per layer which would require a wire diameter tolerance of $\pm 0.033\%$. This is less than the commercial wire tolerance standard and becomes impossible to meet with an insulated wire. The mandrel is therefore grooved with an intentional, small interturn clearance which absorbs the unavoidable diameter variations of the wire and insulation. Small, local variations in overall wire diameter are absorbed easily because adjacent turns can accommodate some deflection which may spread over several turns, but the average diameter should be the same over the whole wire length. Lenders suggests a clearance not exceeding 3% of the wire diameter. The experience here suggests a value between 1 and 1.5%, based on the effect it has on the crossover control. The mandrel grooving is an elaborate effort because the grooves are orthogonal instead of spiral but it assures that the regular winding pattern can be maintained layer after layer. The coils wound in this development had from 18 to 30 layers, depending on their wire diameter.

CROSSOVER CONTROL

In a round coil the crossover line of any layer will form a spiral if left to run freely. At either end of the coil the crossover line of each layer meets the flange at an arbitrary point along the circumference. It has been found that the crossover line of each layer must meet the flange at the same point of the circumference as the underlying layer or the regularity of the winding pattern is lost beginning at that point and continuing on with succeeding layers. Control of the crossovers is necessary to assure the required regular winding pattern throughout the coil. The direct solution is to keep the crossover line straight along the coil axis.

In square or rectangular coils the crossover lines confine themselves to one of the four sides. In a round coil the crossover line can be controlled by utilizing this effect and providing one flat side. The round mandrel has a segment removed and becomes D-shaped. The flat side of the coil shown in Figure 5 is found to be effective in confining the crossovers.

The winding thickness of the crossover part of the coil cross section increases by one wire diameter with each layer. The orthocyclic part increases by only 86.7% of the wire diameter. On the D-shaped mandrel the coil builds up concentrically in the round, orthocyclic part of the cross section but it builds up higher in the crossover part above the flat side. Gradually this flat side becomes round and the coil profile approaches a circle.

On square and rectangular coils three sides with the orthocyclic turns build up essentially flat and one side with the crossovers becomes round.

As the flat side of the coil with the crossovers becomes more nearly round the crossover line begins to run off into the orthocyclic part. Its stability appears similar to that of a sphere on a concave or a flat surface which becomes gradually convex. The confining influence of the flat side disappears. The limit of the crossover control has been reached and the pattern loses its regularity.

One factor influences the crossover line stability significantly: the interturn clearance. As stated before, the crossover line on a round coil tends to form a spiral. The direction of the spiral depends on the lateral forces between the turns. A tight winding pattern causes the crossovers to start earlier with each turn so that the crossover line runs in the direction of the coil rotation. A loose winding pattern causes the crossovers to start later and the crossover line runs

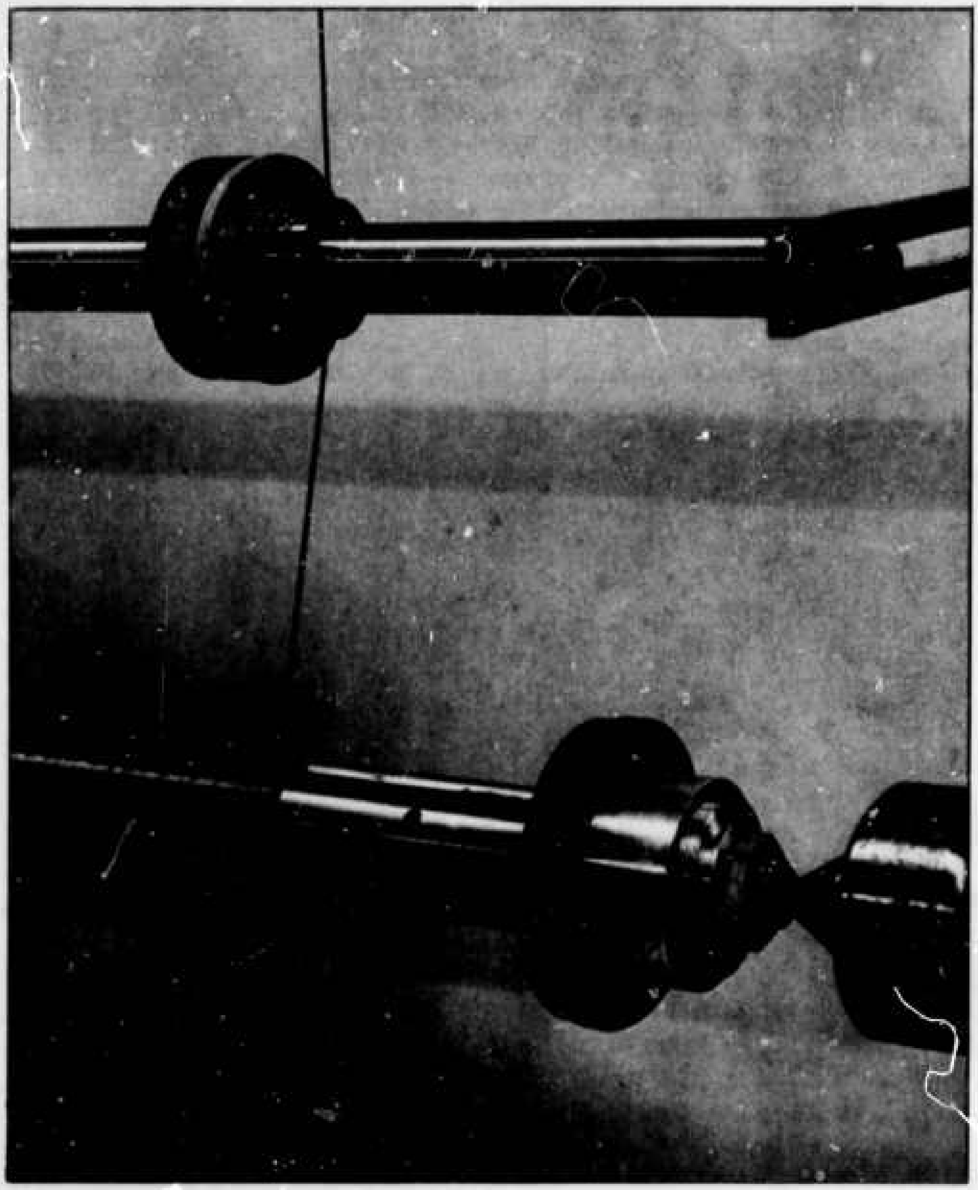

Figure 5. The orthogonal grooving establishes the required regularity of the winding pattern. The flat side of the D-shaped mandrel controls the crossovers and keeps them in line on top of each other in all layers. The freely following sheave on an axis parallel to the mandrel brings a small improvement of the wind behavior with the free-swinging arm. On a regular winding machine the driven level wind consists of a similar sheave but with a controlled lateral advance in accordance with the coil pattern.

against the coil rotation. The flat side of the mandrel forces the crossovers into a straight line but as the flat side becomes round this tendency of the crossover line to run away can take effect. It is here that the selection of the best interturn clearance can delay the runaway condition the longest. This fact emphasizes the importance of a uniform wire and insulation thickness.

Three other factors have an effect on the trend of the crossover line but their effect is not as clearly understood. Increasing hardness and stiffness of the wire appears to have the same

effect as a tighter winding pattern (groove spacing); increasing wire tension appears to cause a looser winding pattern; and increasing winding speed also appears to cause a looser pattern.

The lack of a driven level wind to feed the wire orthogonally to the coil and also the arc of the level wind arm undoubtedly affect the winding performance of this setup. Without a synchronous drive the arm is pulled and trails the winding pattern; it thus contributes to the other factors affecting the trend of the crossover line. The arc of the arm causes the trailing behavior to change to a leading condition at certain times, thus affecting the trend of the crossover line accordingly.

Several factors have been described which affect the crossover trend but which are beyond the control of the operator during the winding process. As soon as their combined effect surpasses the diminishing controlling effect of the flat part of the coil the crossover line begins to run into the orthocyclic part of the coil. The only alternative available during the experiments at this laboratory was to change the groove spacing in search of the best value. The author feels that effective control of the crossover trend can be achieved during the winding process with the help of a synchronously driven level wind mechanism, with its axis parallel to the coil, that can be adjusted to lead, trail or run abreast of the winding pattern. The adjustment is gaged by the operator while winding to oppose any tendency of the crossover line to deviate from the intended straight line.

The winding tension used in the experiments was about 225 kg/cm^2 (3200 psi), based on the conductor cross section. The width of the flat segment of the D-shaped mandrel was made equal to about 90° center angle. A buildup of the coil to an outside to inside diameter ratio of 2:1 was found practicable while still maintaining sufficient control of the crossovers in the flat. Thus about 75% of the coil volume is utilized. The dead soft annealed copper wire was found to be easiest to control.

THE COLLAPSIBLE MANDREL

A collapsible mandrel (Fig. 6) was developed to provide grooving as required for different wire diameters, stiffness during machining and winding despite extreme slenderness, adjustable flanges to fit the end turns of the coil, and collapsibility for removal from the completed and installed coil.

The taper of the four flat mounting surfaces for the grooved bars (tangent of the angle with the shaft axis) is two parts per thousand over the whole length. This small taper was found to be sufficient to permit the shaft to be forced out of the completed coil despite the compression resulting from the winding tension, but the surfaces had to be greased. The bars are fastened to the shaft with recessed screws during turning and grooving. These screws are removed while the first layer is being wound. At the high end the bars extend ¼ in. beyond the taper to form a reaction point for the pulling force on the shaft. This axial pulling force is not transmitted to the coil itself.

The mandrel visible in Figures 2, 4, and 5 has a diameter of 4.2 cm and an overall length of 91.5 cm. A new mandrel is being built with a diameter of 6.1 cm and an overall length of 122 cm.

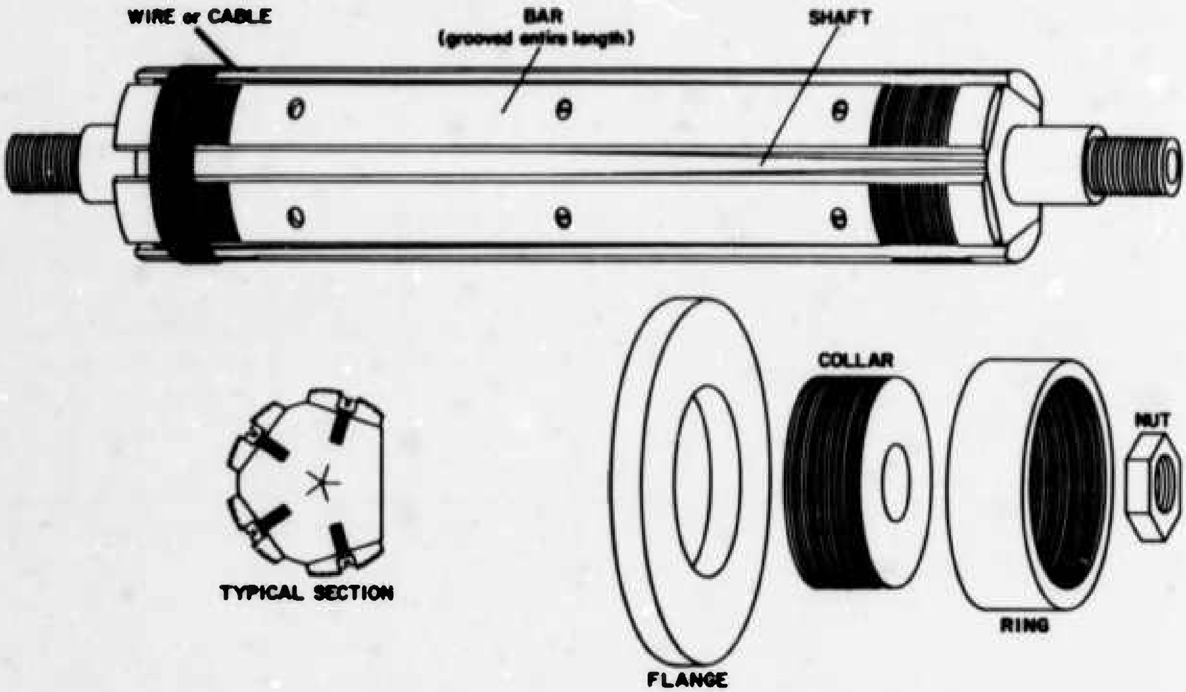

Figure 6. The collapsible mandrel for winding long, slender coils has a solid shaft for stiffness. The four replaceable bars are turned and grooved to the predetermined diameter and groove spacing while mounted. They lie on tapered surfaces to permit extraction of the shaft after winding. The flanges are infinitely adjustable with a threaded ring to fit the groove pattern. The flanges remain with the coil which is secured in a shroud before the mandrel is removed.

CHARACTERISTICS AND APPLICATIONS

The winding technique for long, slender coils has significance in other applications besides thermal probes. Missiles and torpedoes, with similar slenderness for aerodynamic and hydrodynamic efficiency, can contain wires for power, control and/or retrieval, stored in the form of long, slender coils. The regularity of the winding pattern assures reliable payout of the wire and a high packing density.

The orthocyclic winding pattern also produces electrical soil characteristics which are uniformly and consistently reproducible. In long, slender coils these uniform characteristics are desired in variable reluctance devices, traveling wave tubes and other specific applications.

The high quality factor and the compact size of the coils result in an efficiency which may be important in certain solenoid designs.

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13. ABSTRACT

Thermal probes, like certain rockets and torpedoes, contain power and guidance wire for trailing payout. This wire must be wound into long, slender coils to obtain a slim profile, with a winding pattern of high density and perfect regularity to assure reliable payout from inside the mandrel-less coils. The development of a winding capability using the orthocyclic method solved problems of maintaining complete control of the winding pattern throughout the whole coil. A collapsible, grooved mandrel was developed which can be readily removed from the finished coil for reuse. Coils were wound with diameters of up to 8.5 cm and lengths up to 79 cm with wire lengths to 2100 m.

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